PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Improvements in or relating to Well Logging by Nuclear Radiation

We CALIFORNIA RESEARCH CORPORATION, a Corporation duly organised under the laws of the State of Delaware, United States of America, and having offices at 200 Bush Street, San Francisco 20, California, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to nuclear magnetism well logging and, more particularly, is concerned with a method of logging an earth formation wherein the effect of magnetic field inhomogeneities on a nuclear magnetism signal derived from atomic particles, having nuclear magnetic moments, within an earth formation traversed by a well bore are reduced, said signal being used to identify a characteristic of the earth formation, such as the liquids therein, and with an apparatus for carrying out said method.

It is known to log an earth formation, from within a well bore penetrating said earth formation, *inter alia* for the presence of hydrogenous fluids, by a method which comprises the steps of:—

(a) establishing a magnetic polarizing field in said earth formation from within said well bore to polarize the nuclei of hydrogen atoms of hydrogenous fluids within said earth formation, said polarizing field being oriented at an angle to the earth's magnetic field within said earth formation,

(b) interrupting said polarizing field rapidly to permit said nuclei to precess about the earth's magnetic field within said formation,

(c) detecting nuclear magnetic precessional signals from said precessing nuclei, and

(d) measuring a characteristic of the detected precessional signals as an indication of one of the properties of the earth formation. The polarizing field is established by passing a direct current through a field coil positioned in the well bore, the direct current flowing through said polarizing coil until interrupted.

In the techniques briefly outlined above, atomic particles of an earth formation traversed by a well bore are polarized in the magnetic field generated by current flow through a coiled electrical conductor. After the polarization field has been removed and after any subsequent relaxation field, i.e. a field, usually weaker than the polarizing field, used to hold the polarized atomic particles until precession is permitted, has been removed, it is desirable that the particles aligned by the polarization and relaxation fields be subjected to a precession field that is, ideally, spatially uniform. By spatially uniform is meant that the precession field, in the earth formation containing the particles contributing to the spin magnetic induction signals, will be uniform in strength and be parallel at all points in the vicinity of the detector employed to receive the signals of precession. The uniformity of this field is important to the measurement of spin magnetic induction signals because frequency of precession is proportional to the strength of the field in which the polarized protons are to precess. If the precession field is nonuniform, the rate of precession for all particles within a randomly distributed group around the well bore will not be the same. Within the group of precessing particles, therefore, some will soon get out of phase with each other and become so randomly out of phase in their precession that there will be no cumulative signal as there would be if all particles were precessing at the same rate. Summarizing the foregoing then, if the precession field is nonuniform, the spin magnetic induction signal

will be weakened and may even be cancelled.

There are several probable causes of the non-uniformity in the precession field employed to produce the spin magnetic induction logging signal. Of these several causes only two are considered important enough to have a serious effect upon the homogeneity of the precession field. Both causes are based on the probability of magnetizable material in the vicinity of the volume of the formation producing the desired spin magnetic induction signals. One is due to the magnetizable material in the earth formation. The other is due to the magnetizable material in the drilling fluid.

The first of these materials will be magnetized nonuniformly by the strong polarizing field in the initial operation of polarizing. The polarizing field is unavoidably nonuniform because of the apparatus used to establish the field and the position of the atomic particles with respect to the field establishing apparatus. This is an inherent characteristic of a magnetic field created by an electromagnetic coil where the strength of the field may be uniform within the core of the coil but must, of necessity, establish a fanning nonuniformity as the flux lines leave the core and pass around to re-enter the core at the other side of the coil. This polarizing field pattern will establish remnant magnetizations of the material within the formation. That magnetization will persist to produce its own magnetic field, at some greatly reduced strength, but substantially in the direction of the initial polarization field.

The second cause of the field nonuniformity is the magnetically retentive materials in the drilling fluids within the well bore. These materials may be either intentionally placed within the drilling fluid or may be unavoidably included by being chipped or abrasively removed from the drill bit or drill stem in the drilling of the well bore. The drilling fluid could constitute the material within the core of the polarizing coil and will at least surround the coil in its position within the well bore. In those positions it will be subjected to the most intense polarization available from the polarizing coil. Any magnetically retentive materials within the core of the coil will therefore have the probability of producing a relatively large remnant magnetic field having flux lines in the same fanning configuration as was initially produced by the polarizing field. This remnant magnetic field will extend outside of the borehole itself and into the formation to be directionally identical to the polarizing field and will reinforce the previously described nonuniformity established by magnetically retentive materials in the formation.

Throughout this specification the nonuniform fields arising from the above-mentioned causes will be called the extraneous remnant field to distinguish it from the fields such as the earth's field remaining in the formation after the polarizing field has been terminated.

The extraneous remnant field, when superimposed upon the desired uniform precessional field established by the earth's magnetic field, causes the resultant precession field to be nonuniform throughout the formation so that selected polarized particles are acted upon by precession fields of different strength. This variation in precession field strength causes variations in the frequency of precession of individual polarized particles, and the variation in frequency causes a rapid out-of-phasing of the individual signals to reduce the vectorial sum of the total precession signal to a strength below a level of detection. The nonuniformity of the precession field does not affect the time of precession of individual particles to make it so short that it could not be detected, nor does it reduce the strength of any single precession signal; however, because the signal derived from any one particle may soon become out of phase with the signal from another particle, the vectorial summation of all signals soon becomes so small that it cannot be detected and, while this out-of-phase condition may be cylically temporary for a few selected particles, the total effect over the infinitely large whole results in an undetectable signal.

It is an object of the present invention to provide a method of logging an earth formation so as to reduce the effect of magnetized magnetic materials, such as magnetite, on the electrical signal induced in a borehole when protons in an earth formation precess under the influence of the earth's magnetic field after the establishment and interruption of a polarizing field in the earth formation.

In accordance with one aspect of the present invention there is provided in a method of logging an earth formation from within a well bore penetrating said earth formation, the steps of (a) applying a magnetic polarizing field directed at an angle to the earth's magnetic field to a portion of said earth formation by positioning a polarizing field coil in said well bore adjacent to said earth formation and connecting said coil to a source of direct current power so as to cause a direct current to flow through said polarizing coil to polarize nuclear particles in said earth formation, (b) disconnecting said direct current power source from said coil to initiate precession of said polarized nuclear particles, and (c) reducing the effect of the extraneous remnant field (as hereinbefore defined) in said earth formation and/or well bore by controlling the current flow through said polarizing coil after said coil has been disconnected from said source of direct current power during at least the initial time portion of the precession of said polarized nuclear particles so as to effect

the demagnetization of magnetic materials in said earth formation and/or well bore or so as to provide a compensating field of substantially equal and opposite intensity to that of said extraneous remnant field, whereby electrical signals induced in said coil by the in-phase precession of said polarized nuclear particles under the influence of the earth's magnetic field as an indication of physical characteristics of said earth formation can be detected.

Thus, after the polarizing coil has been disconnected from the direct current power source the current flow through the polarzing coil is reversed in direction either instantaneously or after a predeterminable time interval. Before the current is completely stopped in the coil, it may be caused to oscillate while being reduced to zero amplitude so as to demagnetize the magnetic particles causing the extraneous remanent field within the earth formation. The reversed current flow may also be maintained at a substantially reduced amplitude to provide a compensating field opposite in polarity to the field retained by the magnetized magnetic particles. In both of the methods outlined above, the effect of the extraneous remnant field caused by the magnetic particles will be substantially eliminated. The transient electrical signal induced in the well bore by in-phase precession of protons in the earth formation under the influence of the earth's magnetic field and substantially independently of the effect of magnetic materials therein, may then be observed as an indication of a physical characteristic of said formation.

In one embodiment of the invention an alternating current of decreasing magnitude is established in the polarizing coil after a predeterminable time interval so that current flow in the coil is decreased to zero after one or more cycles.

In another embodiment an oppositely polarized current is passed through the polarizing coil after the initial polarization has been terminated. The strength of the oppositely polarized current may be determined from an understanding of the source of the extraneous remnant field. The field nonuniformity is established by the field persisting after polarization caused by the magnetization of naturally occurring magnetizable materials; the elimination of this nonuniformity may then be accomplished by providing a compensating field of equal and opposite intensity in the volume from which spin magnetic induction signals are to be derived. This field is created electromagnetically and, if the source of the field is the same or in the same position as the source of the polarization field, then its pattern will be substantially the same throughout the formation as was the pattern established by the polarization field. The strength of the opposite or compensating field may be determined through successive trials or may be calculated from observations of the envelope characteristics of the spin magnetic induction signals derived from the formation after the application of a compensating magnetic field of preselected strength.

In another aspect, the invention also provides an apparatus, for use in nuclear magnetism well logging, including a logging sonde, means for supporting and moving said logging sonde into and out of a well bore penetrating an earth formation, an electromagnetic coil supported on said sonde, a source of direct current power and visual display means, characterised in that said apparatus further includes a switching device which is adapted (i) to connect and disconnect said electromagnetic coil to and from said source of direct current power for passing and interrupting the flow of a polarizing current through said electromagnetic coil for polarizing the nuclear particles of said earth formation penetrated by said well bore and (ii) to connect said visual display means to said electromagnetic coil after said coil has been disconnected from said source of direct current power, and means for controlling the flow of current through said electromagnetic coil after said switching device has disconnected said electromagnetic coil from said source of direct current power during at least the initial time portion of the precession of said polarized nuclear particles so as to effect the demagnetization of magnetic materials in said earth formatoin and/or well bore or so as to provide a compensating field of substantially equal and opposite intensity to that of the extraneous remnant field in said earth formation and/or well bore, whereby electrical signals induced in said coil by the in-phase precession of said polarized nuclear particles under the influence of the earth's magnetic field as an indication of physical characteristics of said earth formation can be detected.

For a better understanding of the invention, and to show how the same may be carried into effect, reference will now be made, by way of example, to the accompanying drawing in which:

Fig. 1 is a schematic representation of a spin magnetic induction logging tool adapted to carry out the methods of the present invention.

Fig. 2a is a spin magnetic induction signal, in chart form, derived from precessing particles acted upon by an inhomogeneous precession field.

Fig. 2b is a spin magnetic induction signal, in chart form, derived from particles precessing in a substantially uniform precession field.

Fig. 2c is a spin magnetic induction signal, in chart form, derived from particles pre-

cessing in an overcompensated precession field.

Figs. 3a and 3b illustrate representative energization curves for the electromagnetic coil of the logging sonde of Fig. 1.

Fig. 4 is a spin magnetic induction signal, in chart form, derived from precessing particles with operation of the logging tool of Fig. 1 in an alternative method for establishing the overcompensated precession field.

Fig. 5a is a representation of the envelope of a spin magnetic induction signal derived from precessing particles in an overcompensated precession field in accordance with one method of the present invention.

Fig. 5b illustrates an energization curve for a compensating field coil for developing the signal of Fig. 5a.

Fig. 5c illustrates the resultant precession field produced by the application of the energization illustrated in Fig. 5b.

Fig. 6 is an alternative form of the circuitry for energization of the logging sonde for performing the method of the present invention.

Fig. 7 is a schematic representation of another nuclear magnetism logging system adapted to carry out the method of the present invention and illustrates diagrammatically one circuit suitable for the performance of said method.

Fig. 8 is a graph of the polarizing current flow plotted against time, useful in explaining the present method as it may be performed with the apparatus of Fig. 7.

Fig. 9 is a diagram of an alternative electrical circuit useful in the arrangement shown in Fig. 7.

Fig. 10 is a polarizing current versus time graph, similar to Fig. 8 and useful in explaining the operation of the method performed by the apparatus of Fig. 9.

Fig. 11 is a graph of the magnetization of an earth formation plotted against a polarization field strength useful in explanation of the operation of the method of this invention.

Fig. 12 is a circuit diagram illustrating another form of apparatus useful in carrying out the method of the present invention.

Fig. 1 illustrates one form of apparatus for performing the method of the present invention. As illustrated in this figure, the spin magnetic induction well logging measurements are made on a portion of an earth formation 11 lying along a well bore 10 traversing the earth formation 11. In the performance of this method, a coil 12 is supported by and is external to a substantially nonmagnetic logging sonde 13 suspended on a cable 14 from the earth's surface. The logging sonde 13 supports a nonmagnetic form 15 for the coil 12 and houses a switching mechanism for the energization of the coil 12 so that the single coil may be used, as will be hereinafter explained, for polarizing the earth formation 11, for compensating for the effects of the extraneous remnant magnetic fields and for detecting the desired spin magnetic induction signals.

The switching mechanism within the sonde 13 consists of a solenoid 16 having an operating shaft 17 provided with an insulated contact carrier 18 and a flange 19. A spring 21 operates between the flange 19 and the body of the solenoid 16 to bias the contact carrier 18 into the nonenergized position as shown in Fig. 1. Contact carrier 18 is provided at the ends thereof with a pair of contacts 22 and 23 connected by conductors 24 and 25, respectively, to the terminals (not shown) of the coil 12. Four stationary contacts 26, 27, 28 and 29 are provided for the solenoid 16 with the contacts 22 and 23 in engagement with contacts 26 and 27 in the normally unenergized position for the solenoid. The contact carrier 18 is adapted to carry the contacts 22 and 23 into engagement with contacts 28 and 29 upon energization of solenoid 16.

Cable 14 provides not only support for the sonde 13 within the well bore 10 but also encases conductors 31, 32, 33, 34 and 35, carrying the energization and control for the logging sonde from the uphole components of the apparatus at the earth's surface. Conductors 31 and 35 are connected in the logging sonde 13 to the contacts 26 and 27, respectively, and in the uphole components to a power source constituting a battery 36; with conductor 35 connected directly to one terminal of the battery 36 and conductor 31 connected to the other terminal of the battery through a switch 37 with blades 37a and 37b, having operations to be hereinafter defined, and an adjustable resistor 38. Conductor 34 is connected downhole to terminal 29 of the solenoid 16 and uphole to a terminal of a second battery 39 through an adjustable resistor 41. In addition to being connected to battery 36, conductor 35 is connected to a terminal of the battery 39 in the uphole components of the apparatus and, within the sonde 13, to terminal 28 of the solenoid 16 by conductor 42. Conductors 32 and 33 are connected to the solenoid 16 in the downhole components and, uphole, to a battery 43 with conductor 32 being connected to the battery 43 through a switch 44 having contacts 44a for a purpose to be hereinafter defined. The interconnection between the uphole and downhole sections of the conductor 31 to 35 is provided by a slip ring 45 on the cable drum 46 about which cable 14 is wound in raising and lowering the sonde 13 in the well bore 10.

In addition to the control circuitry just described, the uphole components of the apparatus also include an amplifier 47, an oscilloscope 51 and a depth indicator 52. The amplifier is connected to the coil 12 through blocking capacitors 48 and 49 in conductors 31 and

35, respectively, the oscilloscope 51 is driven by the amplifier 47 and may be either an electron-gun type oscilloscope, as shown, or an oscillograph for producing a permanent record of its energization, and the depth indicator is mechanically connected to pulley 53 driven by the cable 14 as the sonde is raised and lowered in the well bore.

The operation of the logging sonde as illustrated in Fig. 1 will now be described. In the preliminary remarks concerning the purpose of the present invention and through the published data on nuclear magnetism well logging, it should be apparent that the coil 12 will be energized to polarize the atomic particles within the earth formation 11 traversed by the well bore 10. In the performance of this polarization function the solenoid 16 will be energized through the contacts of switch 44 to raise the contact carrier 18 thus engaging contacts 22 and 23 with contacts 23 and 29, respectively. Coil 12 will then be connected to the battery 39 to provide energization current as adjusted by resistor 41 to polarize the atomic particles within the earth formation 11. The period for energization of the coil 12 will be previously determined to provide for the proper polarization of the atomic particles within the earth formations being investigated. When switch 44 is opened solenoid 16 will be de-energized to disconnect contacts 22 and 23 from contacts 28 and 29, thus terminating the polarization current to the coil 12, and, under the bias of spring 21, the contacts 22 and 23 will be carried into engagement with contacts 26 and 27 to connect the coil 12 to conductors 31 and 35. In this position the coil 12 is connected through capacitors 48 and 49 to the amplifier 47 and to the oscilloscope 51 to provide a display for the signal generated in the coil 12 upon precession of the polarized atomic particles in the formation.

The polarization of the formation 11 will also entail polarization of magnetizable particles in the formation 11 and in the drilling fluid within the well bore 10. To compensate for the extraneous remnant field which may be produced by the magnetization of the magnetizable particles within the formation and the drilling fluids, coil 12 may be energized with a current flowing in the opposite direction to the current that was employed in the polarization of the formation, thus producing a magnetic field opposite in polarity to that retained by the magnetized magnetizable particles. To provide this energization battery 36 is connected by conductors 31 and 35 to contacts 26 and 27 through switch 37 and adjustable resistor 38. Upon closure of the switch 37, the current supplied by battery 36 will flow through the coil 12 in a direction opposite to the initial polarization current to compensate, in the manner of the foregoing remarks, for the extraneous remnant fields persisting within the formation and drilling fluid.

Figs. 2a to 2c illustrate the spin magnetic induction signals displayed by the oscilloscope 51 upon the receipt of signals at the coil 12 from precessing protons within the formation 11. Fig. 2a illustrates the rapidly decaying signal from the precession of protons within the formation in an inhomogeneous field indicating the rapid out-of-phasing due to the nonuniformity of the precession field for the protons of the formation. A signal of the type as shown in Fig. 2a is of little value for nuclear magnetic resonance well logging purposes due to its brevity making it difficult to detect. In Fig. 2b is illustrated the desirable form of spin magnetic induction signal obtained from the precession of protons in an earth formation. This signal is derived from protons precessing in a substantially uniform field and is, in this case, the type of signal to be derived from earth formation protons precessing in a compensated precession field. In the presentation of Fig. 2b the compensating field, as has been previously defined, is adjusted to be just strong enough to cancel the extraneous remnant magnetic field in the formation to provide the substantially uniform precession field. Fig. 2c illustrates the spin magnetic induction signal derived from precessing protons when the compensating field employed is stronger than that required to just compensate for the inhomogeneities in the precession field due to the previously defined sources. To understand the signal illustrated by Fig. 2c, it is necessary to consider the case of the precession of at least two isolated protons precessing in fields of different strengths. As has been previously indicated, the rate of precession, and therefor the frequency of signal from each proton produced in a coil of the type of coil 12, is dependent upon the strength of the precession field; the stronger the field, the faster the rate of precession. Considering now the two selected protons precessing in fields of different strength with their precessions beginning at the same time, it can easily be seen that after some determinable period of time the proton precessing in the stronger field will have gained a determinable distance of angular movement over the proton precessing in the weaker field. If these protons are spaced equal distances from the coil 12, the vectorial sum of their signals as generated in the coil 12 will start at a maximum when the two are exactly in phase and will gradually decrease to a zero signal when the two are 180° out-of-phase. As the protons continue to precess at the different rates, their individual signals will eventually be brought back into phase to reinforce each other and continue on to an out-of-phase condition, thus developing a sine wave type signal. By expanding the quantity of protons being con-

sidered to the order of their presence within the formations, it is easily understood how, with a randomly nonuniform field, the signal may take the pattern as shown in Fig. 2a as the protons gradually swing out of phase and into a randomly phased condition so that the vectorial sum of the individual signals produced by each proton in the coil 12 will accumulate to a zero signal. On the other hand, with the protons precessing all at the same rate, their signals will produce the sum as is illustrated in Fig. 2b. Returning then to the example of the two selected protons and considering the compensation of the non-uniform precession field by the provision of a current flowing in the opposite direction through the polarizing coil, it may be seen how the signal of Fig. 2b is derived. The signal of Fig. 2c is likewise evident by considering the effect of the application of a compensating field some predetermined time after the termination of the polarizing current derived from the battery 39. If the two selected protons are considered when they have, by their different precession rates, become out-of-phase by some selected angle of rotation, such as 180°, and considering the application of a compensating field stronger than that which would be required to just compensate for the existing extraneous remnant fields, it can be seen that the proton precessing in the weakened field (weakened because the extraneous remnant field at the location of that selected proton is bucking or at least partially bucking the earth's magnetic field, thus reducing the earth's magnetic field) will now have its precession field strengthened to be greater than the earth's magnetic field by the extent of the overcompensation. Under this condition the proton with the strengthened field will have its rate of precession increased so that, with time, it will gain the angular distance it had lost with respect to the other selected proton. At the same time, the other of the selected protons previously precessing under a strengthened precession field (strengthened because the extraneous remnant field at the location of the selected proton is additive or at least partially additive to the earth's magnetic field, thus increasing the earth's magnetic field) will now have its precession field weakened to be weaker than the earth's magnetic field by the extent of the overcompensation. Under this condition, this other proton with its now weakened precession field will have its rate of precession decreased so that, with time, it will lose the previously gained angular distance it had gained with respect to the first selected proton or to a proton precessing at all times in the uniform magnetic field of the earth. Under these circumstances the gradually decreasing signal due to the vectorial combining of signals running out of phase will be reversed and the signal will be gradually increasing as the individual signals come closer and closer to an in-phase condition. The return to the in-phase condition is shown in Fig. 2c by the increase in signal strength at peak B. Continued application of the overcompensating field will merely carry the signal off into out-of-phasing in the opposite direction, causing the signal to gradually decline to a vectorial zero condition.

As has been previously explained, the most desirable condition is to provide a compensating field which will just eliminate the effect of the extraneous remnant field in the formation. The determination of this just-compensating field may be derived from an observation of the effects of the overcompensating field as illustrated in Fig. 2c. By making a permanent record of the pattern as shown in Fig. 2c from the face of the oscilloscope 51 or through the employment of a recording oscillograph, information may be derived which may be applied to the formula as follows:

$$\frac{\text{New Compensating Field}}{\text{First Compensating Field}} = \frac{\text{Time from application of first compensating field to observed envelope maximum (peak B)}}{\text{Time from beginning of precession period to appearance of observed envelope maximum (peak B)}}$$

to indicate the strength of the new compensating field. In the above formula, the first compensating field is the amount of current or a numerical adjustment of the resistor 38 to provide the overcompensated pattern of Fig. 2c; the time from application of first compensating field to observed envelope maximum (peak B) may be measured on the pattern of Fig. 2c as the time from the reversal of the slope of the envelope pattern to the maximum at peak B; the time from beginning of precession period to appearance of the observed envelope maximum (peak B) is easily determined from the pattern of Fig. 2c as a straight axial measurement of distance from the beginning of the signal at point A to the observation of the peak B. The operation of an experiment with the method of the present invention employing an over-compensating field may thus be employed to determine the

precise compensating field required to just compensate for the extraneous remnant fields produced by the magnetizable materials in the formation 11 and in the drilling fluids within the well bore.

In an alternative method of determining the field required to compensate for the extraneous remnant field in the formation an overcompensating field is applied at the beginning of the period of prescession for a predetermined period of time and then the pattern of the precession signal is observed to determine the time for the occurrence of a subsequent signal maximum when the protons have returned to an in-phase condition. An example of this method is shown in Figs. 5a to 5c wherein for a first 10 millisecond period an overcompensating field of minus 500 units is applied to carry the protons rapidly into an out-of-phase condition. In the figure as illustrated the extraneous remnant field in the formation is of the strength of 100 units, thus making the resultant initial overcompensating field a strength of minus 400 units. The ratios of the overcompensating field to the extraneous remnant field are then of the order of minus 4 to plus 1, so that it will take four times as long with the plug field, the extraneous remnant field, to return the protons to their initial phased condition than it took to carry them out of phase. The overcompensating field was applied as shown in Fig. 5b for a period of 10 milliseconds and, applying the ratio of 4:1, the return to an in-phase condition should occur 40 milliseconds later or at the point of the 50 millisecond position on the spin magnetic induction signal envelope pattern of Fig. 5a. Applying the information that may be derived from a presentation of the type of Figs. 5a to 5c to a situation where the extraneous remnant field is unknown but where the time for application and the strength of the overcompensating field is known, the extraneous remnant field may then be determined and a spin magnetic induction signal operation may be performed, employing the exact compensating field necessary to produce a signal of the type illustrated in Fig. 2b.

In Fig. 6 is illustrated an alternative form for a portion of the uphole components of the apparatus of the present invention. With the apparatus of Fig. 6 a relaxation field may be applied to the polarized protons after the polarization field has been applied to bring the protons of the atomic particles within the formation 11 to a desired polarization condition. To accomplish this relaxation polarization, the battery 36 is replaced by a pair of back-to-back batteries 55 and 56, with battery 56 performing the function of the compensation battery 36 in Fig. 1 and battery 55 connected in the same polarity as battery 39 to provide a somewhat smaller polarization current for the relaxation field. A switch 57 is provided to connect conductor 31 to either battery 55 or 56, and a resistor 58 is provided across the back-to-back combination of batteries 55 and 56 to provide a voltage pick-off for the desired polarization current. Switch 57 is provided with a pair of contacts 59 and 61 with contact 59 connected to slider 62 and contact 61 connected to slider 63 to provide respective adjustments for the relaxation field and the compensating field. Switch 57 is operable to either of its extreme positions and is provided with a position in which both the relaxation field and the compensating field voltages are disconnected.

The circuitry of Fig. 6 is provided to produce a polarization pattern as illustrated in Figs. 3a and 3b. In these figures the period between *a* and *b* is the polarization period for the atomic particles within the earth formation. The period between *b* and *c* is the relaxation field and at point *c* the polarization and relaxation are terminated to permit the protons to precess under the desirably uniform earth's magnetic field. The negative parts of the chart for periods *g* indicate the compensating field as applied in Fig. 3a at *e* some time after the period of precession, and in Fig. 3b at *c* immediately at the time precession is begun. The amplitudes of the polarization, relaxation and compensation fields are shown out of proportion in Figs. 3a and 3b to permit all fields to be shown on the charts. It should be understood that the strength of these fields is of the order of 100 units for polarization, 10 units for relaxation, and 1 unit for compensation.

Fig. 7 illustrates an alternative form of apparatus for performing the method of the present invention. As illustrated in Fig. 7, nuclear magnetism well logging measurements are made on a portion of the earth formation 11 lying along a well bore 10. The figure shows a polarizing coil 12 supported by a nonmagnetic logging sonde 13 that may be positioned along the well bore adjacent to the earth formation 11 to be logged. A direct current is supplied to the polarizing coil 12 from a power source such as battery 39 connected to the coil through switching means 16. The direct current flow through the coil 12 establishes magnetization of formation 11 to align or polarize the responsive atomic particles having magnetic moments, such as hydrogen nuclei within that field, including particles within the drilling fluid in the well bore 10. Following such magnetization, current flow from the battery 39 to the coil 12 is normally interrupted by the rapid opening of the switch means 18. With interruption of the polarizing current, continued current flow, due to the inductance of the field coil, is normally reduced to zero as rapidly as possible. Then, the polarized particles in the magnetized earth formation precess under the influence of the earth's magnetic field. To

accomplish the desired precession, it is necessary that the nonuniform magnetization of the earth formation be reduced to substantially zero, with the residual field due to magnetization of mineral grains sufficiently weak, to permit the undistorted earth's magnetic field to interact with the polarized particles in that field. Where magnetic inhomogeneities such as magnetic particles do not exist in appreciable quantity in the earth formation, the interruption of current through the polarizing field coil and the rapid dissipation of current flowing in the coil thereafter, normally permits observation of the electromagnetic signal induced by said precession. This signal is detected either by the polarizing coil connected to a measuring circuit, as in Fig. 7, or by another signal coil (not shown), independent of the polarizing coil, at the same elevation in the well bore.

It has been found in accordance with the present invention that a nuclear magnetism signal of adequate duration and amplitude may be generated even in the presence of magnetic materials by reversal, and where necessary, oscillation, of the polarizing current flowing in the field coil 12 prior to cessation of current flowing therein. In this way, the nuclear magnetism signal may be observed and recorded substantially independently of the magnetic materials in the formation.

For the above purpose, a capacitor 71 is connected in parallel with the polarizing coil 12 so that they form an oscillatory circuit when switching means 18 is opened. The size of the capacitor 71 is desirably selected so that the frequency of oscillating current flowing between coil 12 and the capacitor 71 is substantially higher than the natural precessional frequency of protons in the earth's magnetic field at the point under investigation. Desirably this frequency is somewhat higher than two kilocycles.

The operation of the circuit of Fig. 7 is particularly illustrated in the graph of Fig. 8. As there shown, the polarizing field coil current is applied for a predetermined time interval by holding closed switch 18. Switch 18 is desirably of the vacuum type to reduce arcing between the contacts when abruptly opened. Supply of power from the battery 39 to polarizing coil 12 is then interrupted at the time indicated in Fig. 8. When switch 18 is thus opened, current flow from polarizing coil 12 continues in the same direction for a short time due to its internal inductance. Then capacitor 71 becomes charged so that said current flow is then reversed in direction and oscillates through a number of cycles. The number of said cycles, of course, is determined by the time constant of the LRC circuit formed by coil 12 and capacitor 71. Since the duration of the oscillating field must be less than the decay time of the measured signal, the time constant of the circuit must be made quite short.

As shown in Fig. 8, the current in field coil 11 after several reversals is brought to substantially zero within a predeterminable time interval. The effect of such current reversal is best understood by reference to Fig. 11, where magnetization of the formation has been plotted against the polarizing field as represented by current flow in polarizing coil 12. As shown by the curve of Fig. 11, it will be noted that the magnetic hysteresis loop is gradually reduced, so that the remaining magnetization of the formation, and especially the particles of magnetic materials having large susceptibilities will be reduced to substantially zero after said reversal. In accordance with the present invention, said demagnetization of the earth formation, however, does not appear to greatly affect the electromagnetic signal induced by the gyromagnetic particles, measured as an indication of one of the properties, or characteristics, of the earth formation. In particular, the signal induced by in-phase precession of protons under the influence of the earth's magnetic field is particularly indicative of the liquids in the earth formation. Identification of the liquid content, or the distinction between water and hydrocarbons in said formation, is thus derived from the amplitude of the electrical signal as measured for various duration times of the polarizing current.

Referring now to the arrangement of Fig. 9, there is shown an alternative form of apparatus to the circuit shown in Fig. 7. A nonlinear resistor 72, such as thyrite, is desirably connected in parallel with the polarizing coil 12, and if an external capacitance, such as parallel capacitor 71 is employed, the resistor is likewise in parallel thereto. The purpose of the thyrite resistor 72 is to control decay of polarizing current in coil 12 as particularly shown in the diagram of Fig. 10. As there seen, the thyrite resistor 72 serves to absorb and dissipate the residual current from polarizing coil 12, after the current to the polarizing field coil is interrupted by opening switch 18. It is to be noted that the magnetizing current is permitted to decrease on a ramp function of relatively long time delay. When the potential across nonlinear resistor 72 approaches its threshold value, the condenser 71 and field coil 12 interact to set up an oscillatory polarizing current flow through the field coil. This is illustrated by the reversal in the polarizing field illustrated as a decaying a.c. signal in the right-hand portion of Fig. 10.

With the arrangement of Fig. 9 there is made possible observation of the signal induced in the well bore by precession of polarized particles, after the polarizing field has been gradually reduced to zero. This system provides an alternative method to that disclosed in connection with Fig. 7. In the

Fig. 9 system, the polarizing current in the field coil 12 need not be removed as rapidly as in the Fig. 7 system to permit observation of the precession of polarized particles in an earth formation having magnetic inhomogeneities. The system shown in Fig. 9 is preferable where a great deal of magnetic material is present in the formation rock. Alternatively, a plurality of constant potential tubes, such as cold cathode tubes, may be substituted for the thyrite resistor 72.

In the arrangement of Fig. 12, there is illustrated another form of apparatus for carrying out the method of the present invention. The system of Fig. 12 includes a multiple switching arrangement for periodically, or cyclically, reversing the polarizing current flowing in the field coil after initial interruption of the main current source, battery 39. As here illustrated, the successive potentials of decreasing amplitude are supplied to polarizing coil 12 by switch 73. The contacts 74 of switch 73 are connected to potentiometers 75 and 76 having taps 77 and 78, respectively, on batteries 39 and 40. These taps are proportioned with respect to the inductance and resistance of the polarizing coil so that there is generated the desired reversal of current flow through said coil 12. It will thus be seen that there is made possible the desired reversal and alternating of potential across the polarizing coil to demagnetize the magnetic particles, whether in the earth formation under investigation or in the borehole fluid.

The recording system as shown in Fig. 7 provides means for indicating at the earth's surface one of characteristics of the induced electrical signal for correlation with the depth of logging sonde 13 and polarizing coil 12 in the well bore 10. As particularly shown in Fig. 7, the depth of coil 12 is recorded by depth meter 52 driven by cable 14. The electrical signal may be recorded photographically, as by camera 81, which is positioned to record both the depth measurement on recorder 52 and the electrical signal displayed on the face 83 of cathode ray tube 84. As indicated schematically, the horizontal deflection of the cathode ray beam in tube 84 is generated as a function of time by horizontal deflection amplifier 85. The vertical deflection of the beam corresponds to both the amplitude and the frequency of the signal supplied by amplifier 86. Amplifier 86 is connected to coil 12 through line 31, while current flow from source 39 over line 34 is interrupted.

In the operation of the polarizing circuit including vacuum switch 18, solenoid 16 is remotely operated by switch means 44 in response to timing motor 87 and cam 88. It will be seen that the switch 44 operates to connect solenoid 16 to a power source, such as battery 43, through lead 32 of cable 14 and to a ground return including the drilling fluid and the mud pit. In this arrangement, switch 44 opens and closes cyclically, as the polarizing coil 12 is positioned opposite a formation to be logged. Cam 88 closes switch 44 for a predeterminable time interval and then the current flow in the polarizing coil is controlled to return to zero, or to some predetermined current flow of opposite polarity. As further shown in Fig. 7, cam 88 may be arranged to close and open switch 44 and vacuum switch means 18 so that the polarizing current flows for two different periods of time. These periods of time are selected so that one is quite long as compared to the other. Thus, the thermal relaxation time of the induced signal may be derived from signal intensity as a function of polarizing time.

WHAT WE CLAIM IS:—

1. In a method of logging an earth formation from within a well bore penetrating said earth formation, the steps of (a) applying a magnetic polarizing field directed at an angle to the earth's magnetic field to a portion of said earth formation by positioning a polarizing field coil in said well bore adjacent to said earth formation and connecting said coil to a source of direct current power so as to cause a direct current to flow through said polarizing coil to polarize nuclear particles in said earth formation, (b) disconnecting said direct current power source from said coil to initiate precession of said polarized nuclear particles, and (c) reducing the effect of the extraneous remnant field (as hereinbefore defined) in said earth formation and/or well bore by controlling the current flow through said polarizing coil after said coil has been disconnected from said source of direct current power during at least the initial time portion of the precession of said polarized nuclear particles so as to effect the demagnetization of magnetic materials in said earth formation and/or well bore or so as to provide a compensating field of substantially equal and opposite intensity to that of said extraneous remnant field, whereby electrical signals induced in said coil by the in-phase precession of said polarized nuclear particles under the influence of the earth's magnetaic field as an indication of physical characteristics of said earth formation can be detected.

2. A method according to Claim 1, wherein the current flow through said polarizing field coil after the coil has been disconnected from said source of direct current power is controlled by successively reversing the direction of flow of current through said polarizing field coil so as to establish an alternating current of decreasing amplitude for at least one cycle prior to cessation of current flow through said coil.

3. A method according to Claim 2, wherein said reversal of current flow is effected by

applying an alternating potential of decreasing amplitude to said polarizing coil.

4. A method of logging an earth formation from within a well bore penetrating said earth formation according to Claim 1, substantially as hereinbefore described with reference to the accompanying drawings.

5. An apparatus, for use in nuclear magnetism well logging, including a logging sonde, means for supporting and moving said logging sonde into and out of a well bore penetrating an earth formation, an electromagnetic coil supported on said sonde, a source of direct current power and visual display means, characterised in that said apparatus further includes a switching device which is adapted (i) to connect and disconnect said electromagnetic coil to and from said source of direct current power for passing and interrupting the flow of a polarizing current through said electromagnetic coil for polarizing the nuclear particles of said earth formation penetrated by said well bore and (ii) to connect said visual display means to said electromagnetic coil after said coil has been disconnected from said source of direct current power, and means for controlling the flow of current through said electromagnetic coil after said switching device has disconnected said electromagnetic coil from said source of direct current power during at least the initial time portion of the precession of said polarized nuclear particles so as to effect the demagnetization of magnetic materials in said earth formation and/or well bore or so as to provide a compensating field of substantially equal and opposite intensity to that of the extraneous remnant field in said earth formation and/or well bore, whereby electrical signals induced in said coil by the in-phase precession of said polarized nuclear particles under the influence of the earth's magnetic field as an indication of physical characteristics of said earth formation can be detected.

6. An apparatus as claimed in Claim 5, wherein said switching device includes means for connecting to said electromagnetic coil a second source of direct current power of polarity opposite to said polarizing source of direct current power, whereby the electromagnetic coil may be energised to apply a compensating field to said nuclear particles and to said magnetic materials in a direction opposite to the polarizing field and in magnitude equal to the magnetic field produced by said magnetic materials.

7. An apparatus as claimed in Claim 5, wherein said means for controlling the flow of current is an oscillatory circuit including the electromagnetic coil and a capacitance, whereby an alternating current of decreasing amplitude will flow through said coil after said coil has been disconnected from said polarizing source of direct current power, so that the effect of the polarizing field on magnetic materials in said earth formation is substantially minimised.

8. An apparatus as claimed in Claim 5, wherein said switching device connects a first current control means to said electromagnetic coil when said coil is disconnected from said source of power, said first current control means being operative to decrease the amplitude of said source of power to substantially zero in a predeterminable time interval, and further control, means connected in circuit with said electromagnetic coil to oscillate current flow therethrough and to decrease the amplitude thereof to a predeterminable value.

9. An apparatus as claimed in Claim 5, wherein the means for controlling the flow of current includes another source of direct current power and said switching device for alternately connecting said coil to the first named source and said other source in opposite polarities, the arrangement being such that an alternating current flow of decreasing amplitude is produced in the electromagnetic coil when said first named source has first been disconnected.

10. An apparatus as claimed in Claim 5, wherein the means for controlling the flow of current is an oscillatory circuit including the electromagnetic coil, a non-linear resistance and a capacitance, the arrangement being such that, when the switching device disconnects said electromagnetic coil from said polarizing source of direct current power, the oscillatory circuit produces a current in the coil which current initially decreases substantially to zero in a predeterminable time interval owing to the action of the non-linear resistance and which current thereafter oscillates with decreasing amplitude.

11. An apparatus as claimed in Claim 5, substantially as hereinbefore described with reference to, and as shown in, Figures 1, 6, 7, 9 and 12 of the accompanying drawings.

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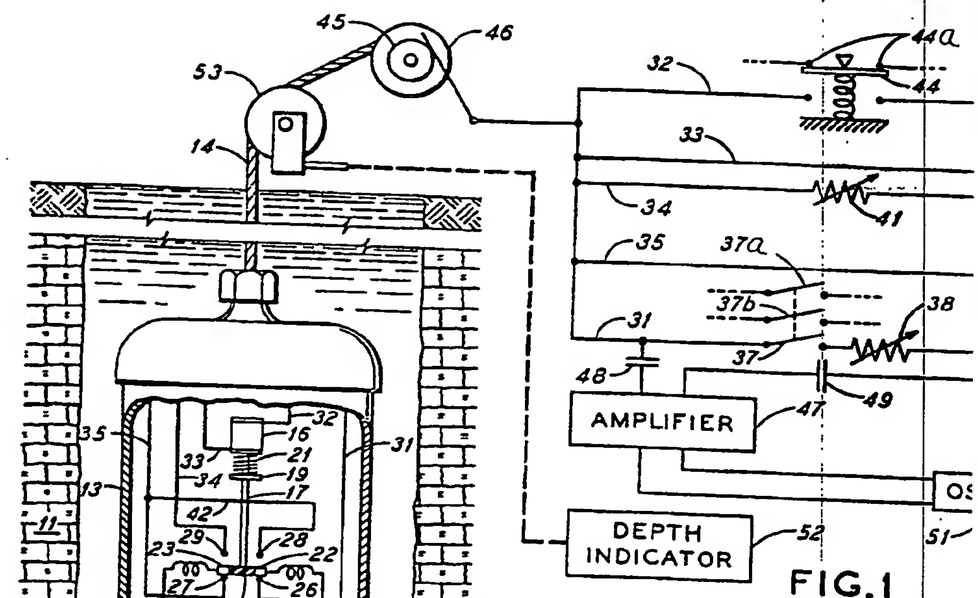

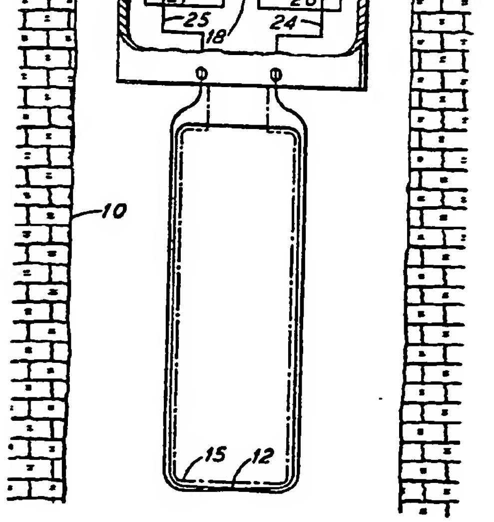

FIG.1

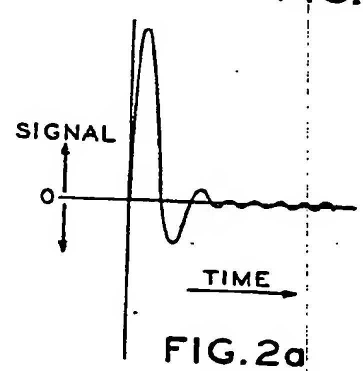

FIG.2a

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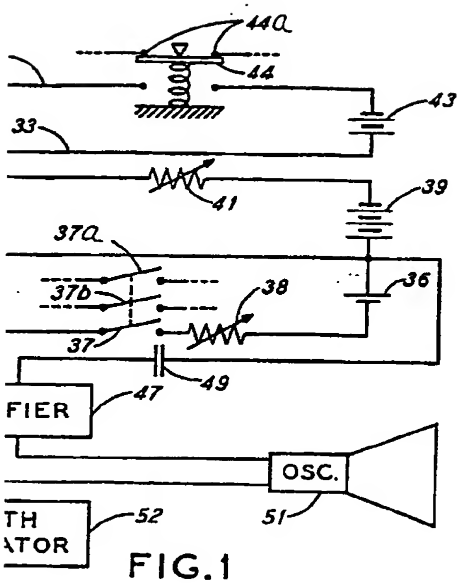

FIG.1

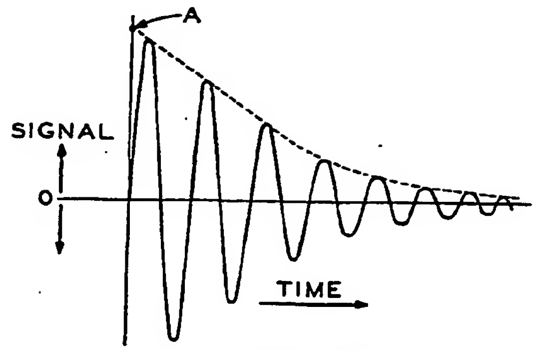

FIG. 2b

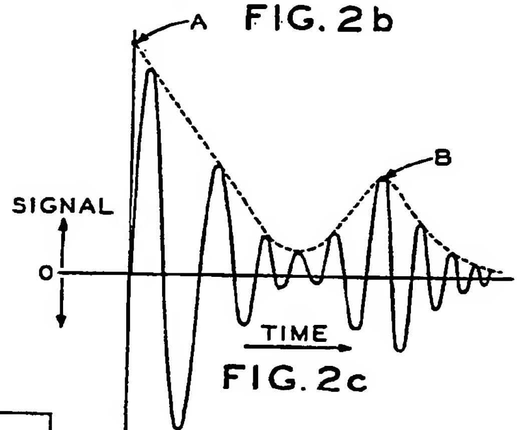

FIG. 2c

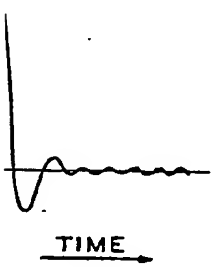

FIG.2a

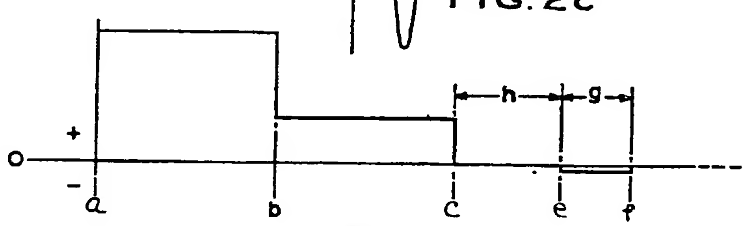

FIG. 3a

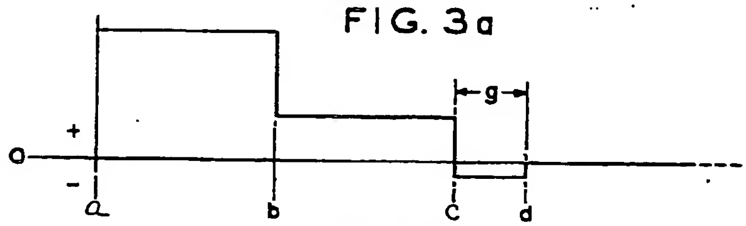

FIG. 3b

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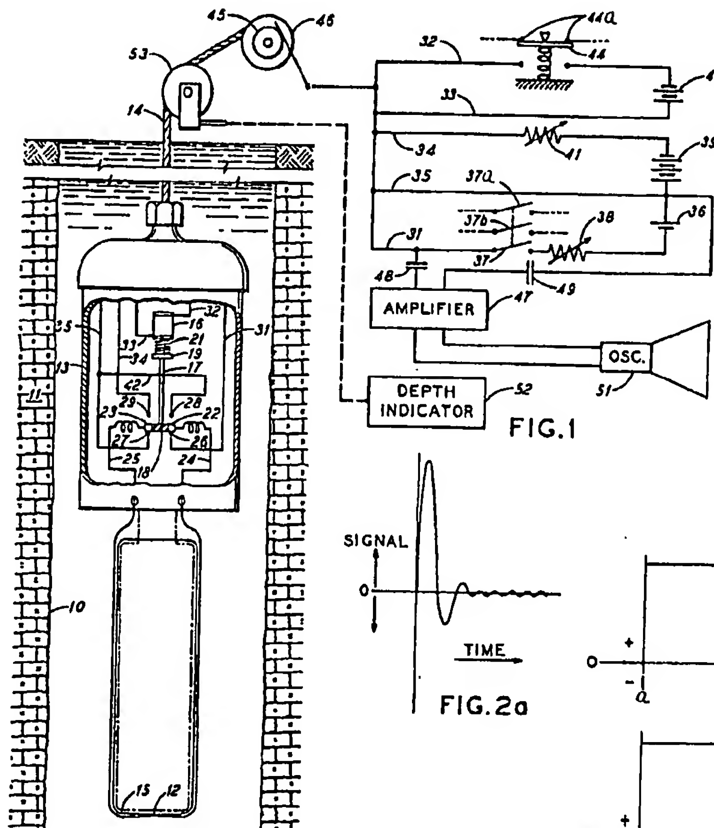

FIG.1

FIG.2a

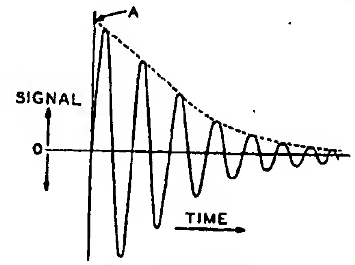

FIG.2b

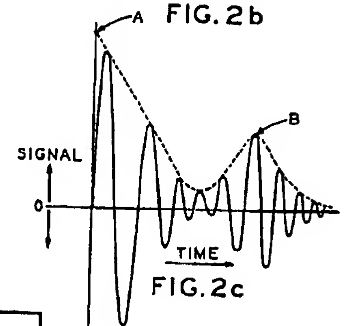

FIG.2c

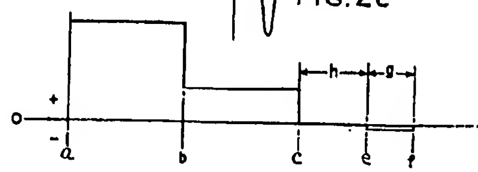

FIG.3a

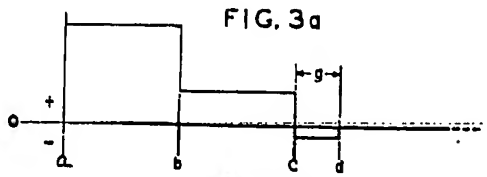

FIG.3b

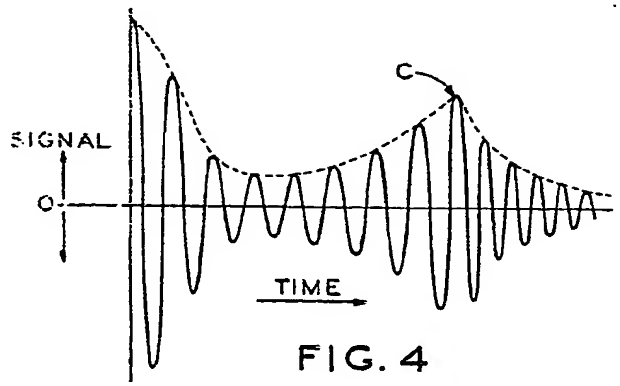

FIG. 4

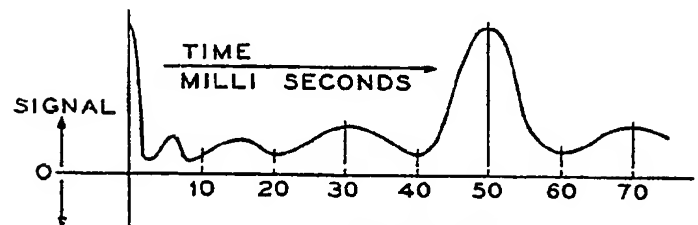

FIG. 5a

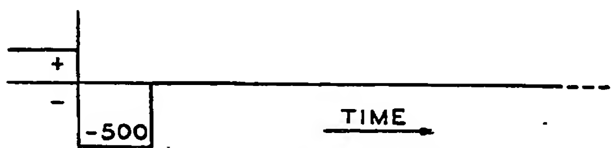

FIG. 5b

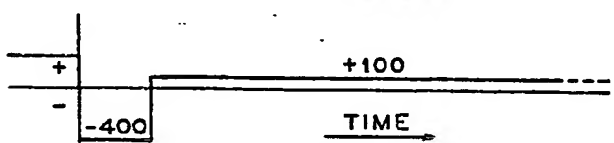

FIG 5c

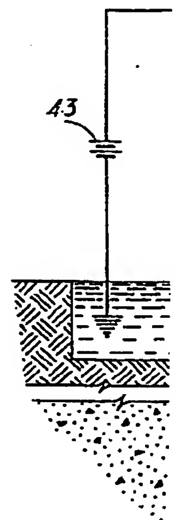

FIG.7

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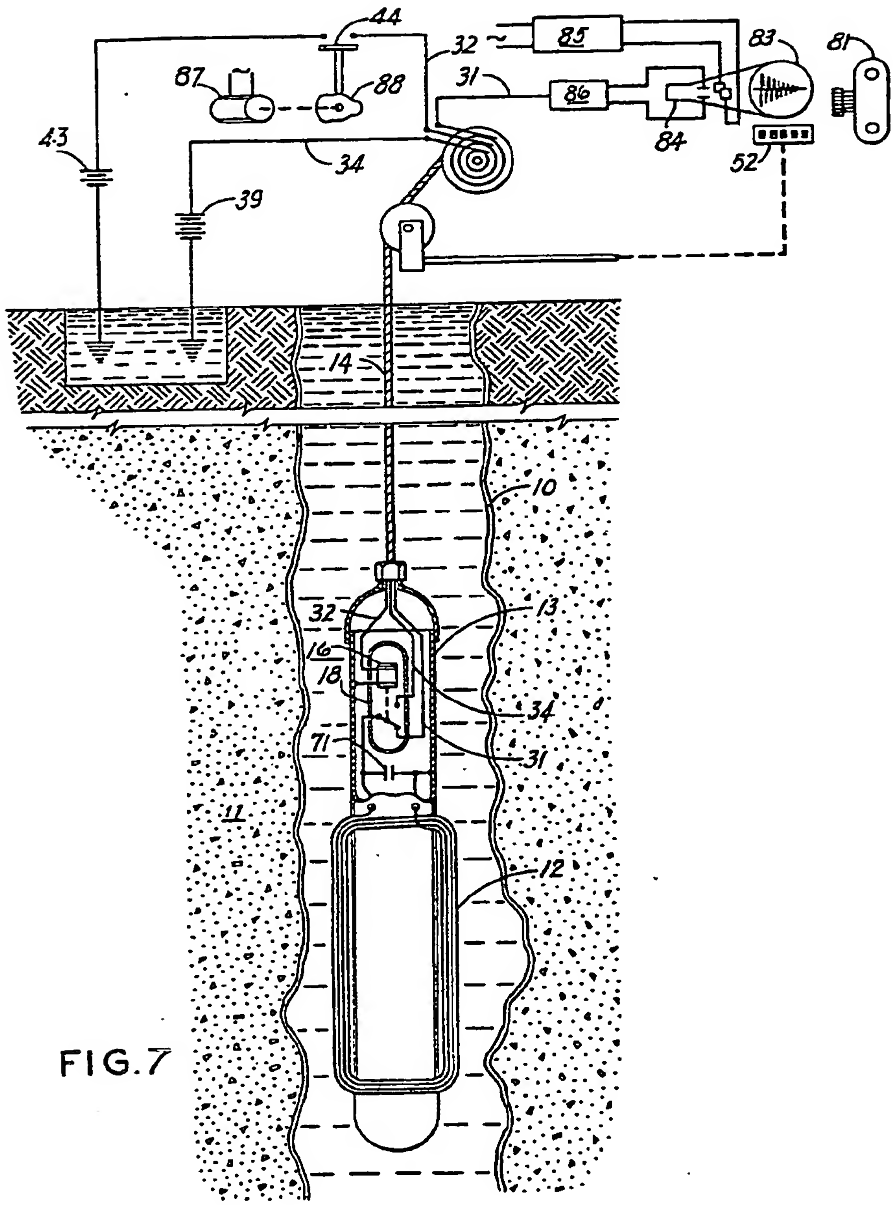

FIG.7

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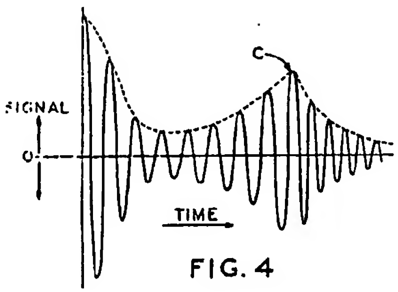


FIG. 4

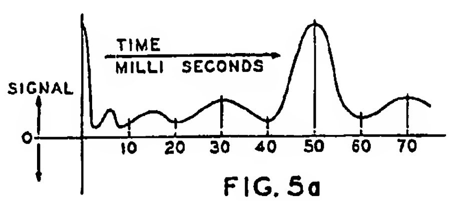


FIG. 5a

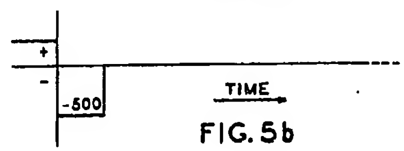


FIG. 5b

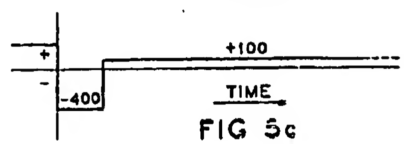


FIG 5c

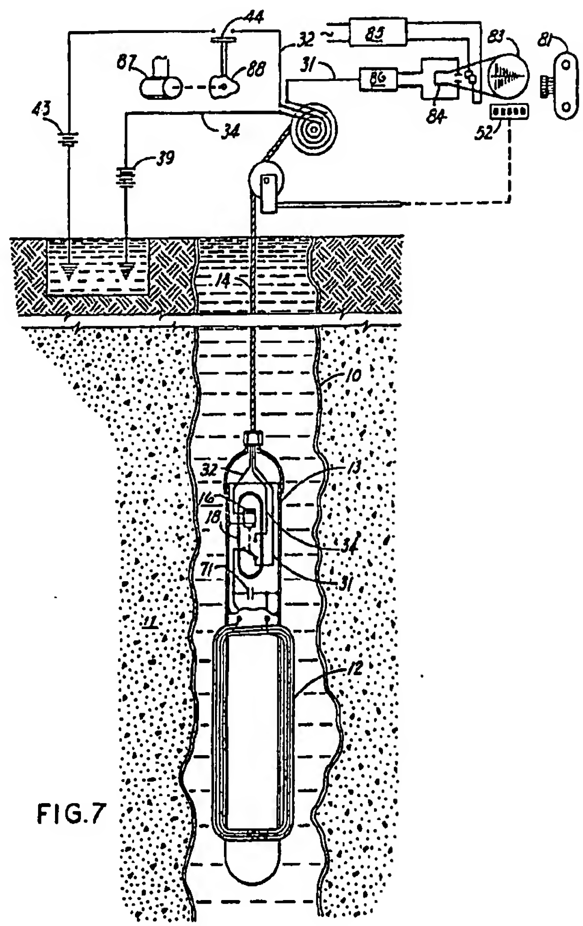


FIG.7

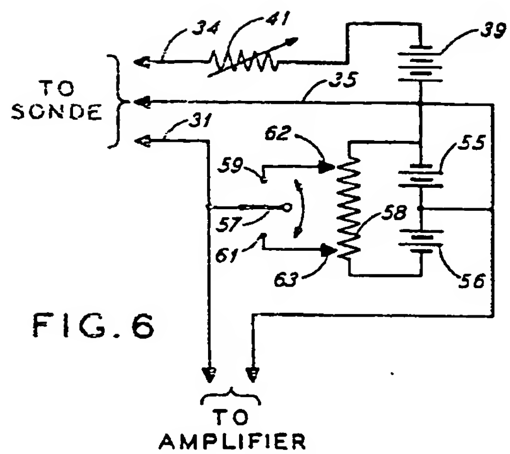


FIG. 6

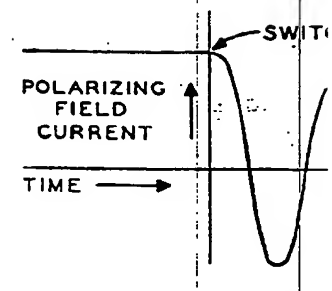


FIG.

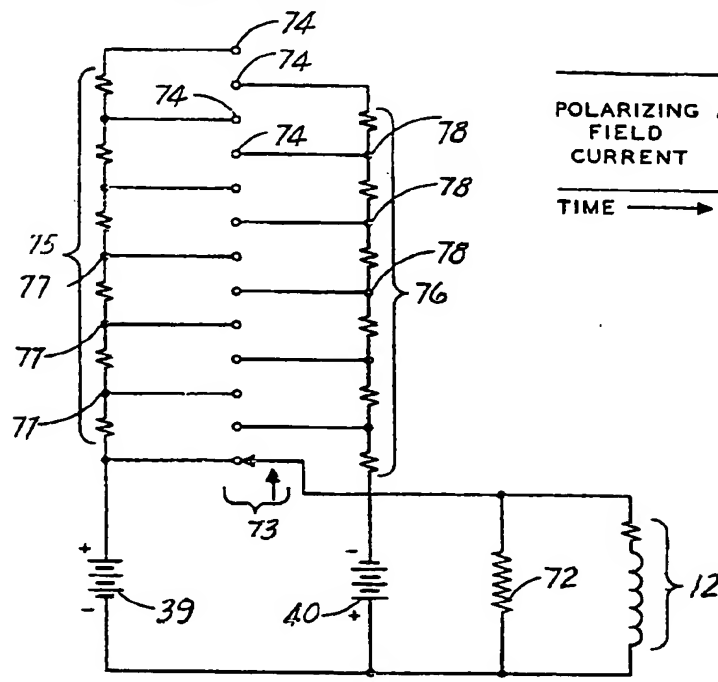
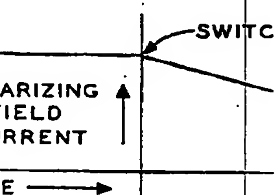


FIG. 12



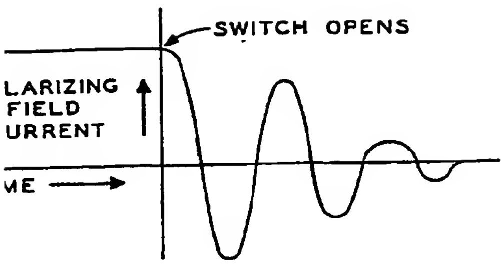


FIG. 8

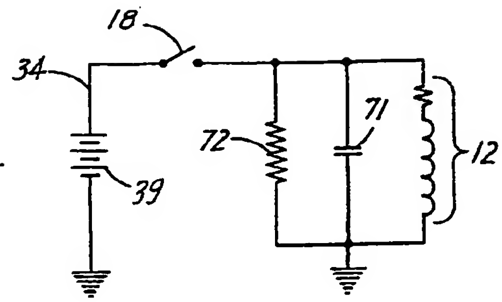


FIG. 9

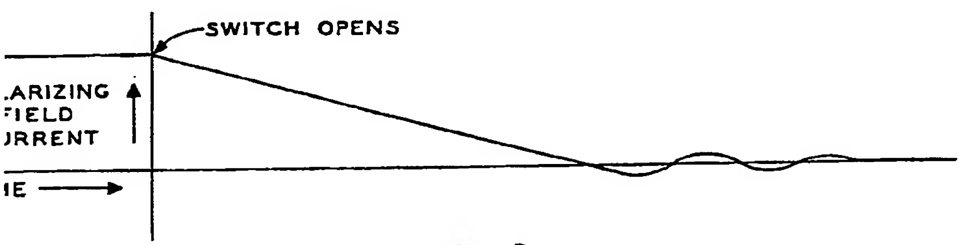
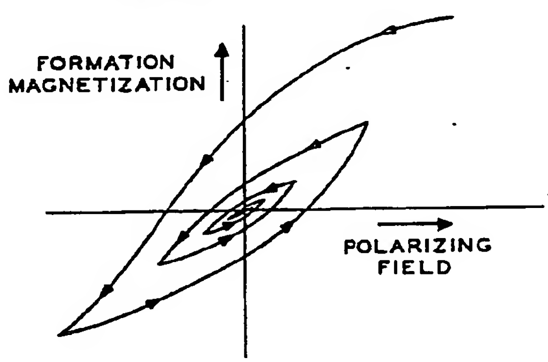


FIG. 10



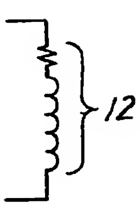


FIG. 11

1002540 COMPLETE SPECIFICATION
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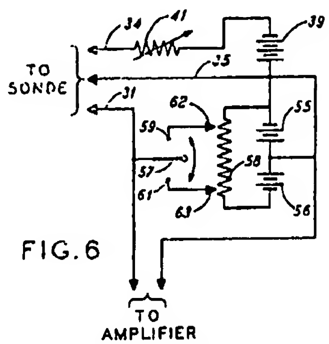

FIG. 6

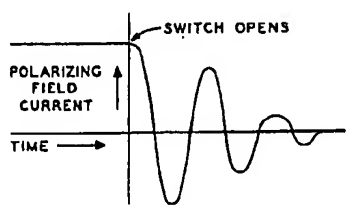

FIG. 8

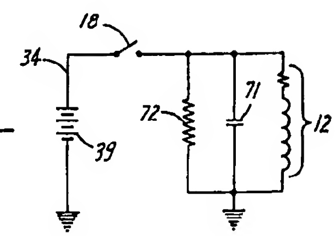

FIG. 9

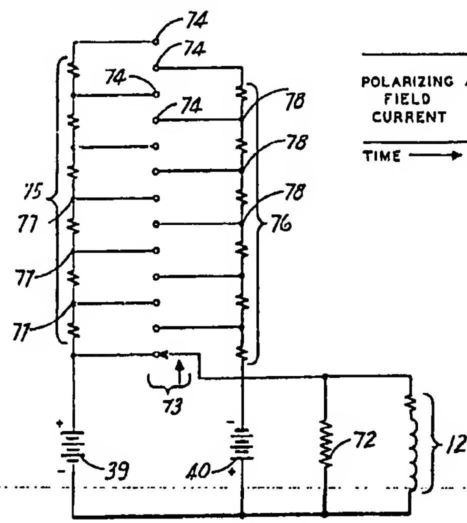

FIG. 12

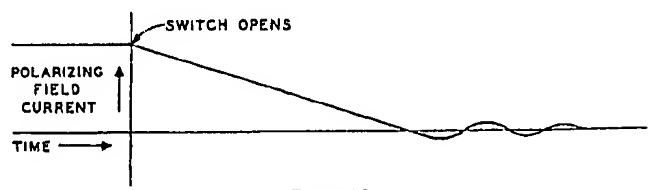

FIG. 10

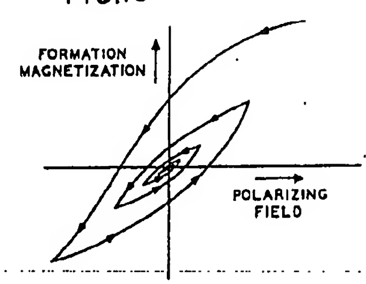

FIG. 11